Instant Air Meter Measurement of Air Content in Fresh Concrete

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Corporate Profile

- Contract Engineering R&D
- Hanover, NH
- Industrial and Federal Client Base
- Founded in 1961
- Owned by Partnership of Engineers

160+ Employees
- 70+ Engineers (55% Ph.D., 30% M.S.)
- 40 Technicians, Machinists, Drafters (30% B.S., 30% A.S.)

Technology Commercialization
- Licensing
- Spin-Off Companies
- Custom Products
Creare Spin-Offs Employ 2,300 and Generate Over $475M in Annual Revenues
Overview

• **SWAM** – Shock Wave Air Meter
  - **Total Air** and **Specific Surface** in fresh concrete
  - More accurately predict **Hardened Spacing Factor**
  - Handheld
  - Instantaneous

• Improve QC
  - Quality
  - Frequency
Technology Status

- Early Development
- One Prototype, In Flux
- Seeking Industry Feedback and Input
Concrete Air Quality

Air voids in hardened concrete are critical for freeze-thaw durability; Voids give expanding water a place to migrate into.
Air Void Parameters

Number Density: \( n = \# / \text{in}^3 \)

Total Air: \( VF = nD^3 \)

Specific Surface: \( SS = \frac{D^2}{D^3} = \overline{D}^{-1} \)

Spacing Factor: \( SF = \overline{L} \approx \frac{PF}{SS \cdot VF} \)

- **Spacing Factor is what matters**
  - Target typically \( SF \leq 0.008” \)
- Cannot measure SF fresh
- Can infer by measuring VF and SS
- In static concrete, SF more likely to be stable
  - When bubbles grow/shrink, VF and SS move in opposite directions

Snyder, Adv Cem Bas Mat, 1998
Existing Measurement Methods

• Hardened Petrographic Analysis
  ➢ ASTM C457
  ➢ Expensive, delayed

• Fresh Air
  ➢ ASTM C231 Pressure
  ➢ ASTM C138 Gravimetric
  ➢ ASTM C173 Volumetric

• Fresh, Additional Parameters
  ➢ Germann AVA-3000
  ➢ Super Air Meter
C231 Pressure Meter most common
• Trained technician, 5–10 minutes
• Ideal accuracy: ~ ± 0.8 percentage points
• Correlation to hardened air:
  ~ ± 2 percentage points
• SF prediction uncertainty > ± 0.004” (100 μm)

Saucier, Pigeon, and Cameron, ACI Mat. J. (1991)
AVA – Predicting Hardened Properties

- Poor correlation to hardened
- Uncertainty (bias-corrected):
  - **Air:** $> \pm 2$ percentage points
  - **SS:** $> \pm 250$ in.$^{-1}$ (10 mm$^{-1}$)
  - **SF:** $> \pm .004$ in. (100 $\mu$m)

AVA - Predicting Hardened Spacing Factor

- Very weakly correlated
- Uncertainty (bias-corrected): $\sim \pm 0.008''$ (200 $\mu$m)


Problem Summary

• What matters (physically) is **Hardened Spacing Factor**
  - Typical target \( \leq 0.008" \)
  - Need to predict when fresh

• Fresh Air – Pressure Meter
  - 5–10 minutes, effortful, tedious
  - Hardened Spacing Factor uncertainty \( \geq 0.004" \)

• AVA
  - 25 minutes, mortar separated by agitation
  - Hardened Spacing Factor uncertainty \( \pm 0.004 - 0.008" \)

• Super Air Meter
  - 10 minutes, more tedious
  - Tanesi, FHWA (2016): “… better correlation between fresh air content and spacing factor than … between SAM number and spacing factor”
SWAM Instrument
Principle of Operation

- Piston coupled to fresh concrete
- Shock wave launched into the concrete
- We measure a compressibility and relaxation time parameter
- Compressibility related to total air
  - Bubbles are squishy!
- Relaxation time related to bubble size (specific surface)
  - Small bubbles respond quickly
  - Large bubbles take more time
SWAM Use
Test Matrix

- Georgia Tech – Kim Kurtis, Scott Smith
- 83 total mixes, typical of transportation projects

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Category #1: 64 Mixtures</th>
<th>Category #2: 9 Mixtures</th>
<th>Category #3: 8 Mixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/cm (lb/lb)</td>
<td>0.40, 0.45, 0.50, 0.55</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Design Air Content (%)</td>
<td>2, 4, 6, 8</td>
<td>4</td>
<td>4²</td>
</tr>
<tr>
<td>Coarse Aggregate Volume</td>
<td>0.62, 0.70</td>
<td>0.62, 0.66, 0.70</td>
<td>0.66</td>
</tr>
<tr>
<td>Fraction (%/100)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMAS (in) (Gradation (#))</td>
<td>1” (#57),</td>
<td>0.75 (#6), 1 (#57), 1.25 (#4)</td>
<td>#57</td>
</tr>
<tr>
<td>SCM Type</td>
<td>N.A.</td>
<td>N.A.¹</td>
<td>Class F and C Fly Ash, Limestone Powder, Slag²</td>
</tr>
<tr>
<td>SCM Replacement (% wt. of OPC) (%)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>20 and 40</td>
</tr>
<tr>
<td>Admixture Combination</td>
<td>AEA, AEA + WRA</td>
<td>AEA</td>
<td>AEA</td>
</tr>
</tbody>
</table>

1. For replicate mixtures from Category #1, OPC will be replaced by Class F Fly Ash by 20% by mass.
2. For replicate mixtures from Category #2, design air content will be 6%.
Achieved Air Diversity

ASTM C457 Petrographic Results

Specific Surface (1/in.) vs. Total Air (%)

Spacing Factor (in.)

- 0.015
- 0.01
- 0.005
Hardened Air

Pressure Meter

Fresh Air, ASTM C231 Pressure Meter (%) vs Hardened Air, ASTM C457 (%)

- $R^2$: 0.66
- Std Err: 1.4%

SWAM

Fresh Air, SWAM (%) vs Hardened Air, ASTM C457 (%)

- $R^2$: 0.67
- Std Err: 1.4%
Feasibility Results

- 14 concrete samples
  - 3/8” aggregate
  - 30% paste
  - Constant slump
  - Only one variable: AE admixtures

- SWAM
  - 3 insertions, 3 measurements
  - 2 different days

![Void Fraction](image1)

![Specific Surface](image2)

- Void Fraction
  - \( R^2: 0.88 \)
  - Std Err: 0.63%

- Specific Surface
  - \( R^2: 0.97 \)
  - Std Err: 38 in.\(^{-1}\)
• Traced problem to faulty O-ring in critical subsystem
• Initial laboratory testing with improved O-ring are encouraging
Summary

• **SWAM:**
  - Hardened Air
    - Standard error: ~1.4 percentage points
    - Similar to pressure/gravimetric methods
  - Hardened Spacing Factor
    - Standard error: ~0.003"
    - Slightly superior to existing fresh methods (AVA)
  - Quick, simple
  - Will get better:
    - More accurate specific surface → more accurate spacing factor
    - Battery powered, real-time display
    - Bluetooth / QR codes for data logging
Discussion

• Next Steps (2 years):
  ➢ Fix O-ring (and other) issues and validate
  ➢ Add user interface
  ➢ Produce several “real” prototypes
  ➢ Industry and DOT field trials
    – Always looking for potential field test opportunities
Elastomer Calibration Articles

No Air  Moderate Air  More Air